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Discussions

Interactive comment on "Tectonic Exhumation of the Central Alps Recorded by Detrital Zircon in the Molasse Basin, Switzerland" *by* Owen A. Anfinson et al.

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Author Comments for:

Tectonic Exhumation of the Central Alps Recorded by Detrital Zircon in the Molasse Basin, Switzerland

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Reviewer comments from Jan Wijbrans (RC1) and associated Author Comment (AC1)

RC1- 1- As zircon often is quite robust small signals from all these periods have been

recovered. Although the paper is quite extensive in its citing of previous work, at this stage I am missing an important paper: that of Gebauer et al. in the Swiss Petrographoische and Mineralogische Mitteilungen (1988" v: 68, pg 485-490) which reports Archean zircons in a retrograde Caledonian eclogite from within the Gotthard Massif, as probably the first report of Precambrian provenance of recycled zircons from Switzerland.

AC1-1- We have added a brief note about the Gebauer ages (section 2.2.2) and have included the citation.

RC1-2- There is a clear divide where significant amounts of Austro-Alpine cover was exposed in the hinterlands and where it ceased to contribute sometime around 21 Ma ago. This aspect is discussed in the paper, but to my mind the discussion could be pushed further.

AC1-2- We have added content to this discussion in section 8.2.

RC1-3- A positive link between this age signal and the eroding Variscan basement could have been made by presenting a a compilation of U/Pb zircon ages from in situ rocks from the external massifs and their enveloping metamorphics.

AC1-3- We have compiled DZ data from modern river sediments derived from the Lepontine Dome. These ages provide spectra of what is presently being derived from the region. This provides the modern structure and avoids compilation of hundreds of in-situ ages across the central alps. We include this discussion in section 8.1.

RC1-4 The other point that perhaps should be developed somewhat further is the zircon provenance of the signal in the lower units, attributed to eroding Austro-Alpine cover. This easily made first point of course is that the provenance f zircons in these units is dramatically different than that of the upper units and reflect formation in a domain geographically removed from the European Variscan crystalline basement.

AC1-4- We have increased the discussion of the provenance signal of the lower units, and have included a modern river sample that displays an approximate AustroAlpine DZ age spectra in Figure 1 (Adda @ Dubino). We have listed references for hard rock age data but feel presentation of these data overwhelm the presented data set with too many comparison age spectra.

RC1-5- The question is where was the Adria plate where it could incorporate Panafrican-Cadomian aged zircons and Caledonian aged zircons in addition to a fundamentally different spectrum of Variscan ages when compared with the spectrum of the younger rocks that reflect European crystalline middle crust?

AC1-5- The Austroalpine ages are relatively well known and in-depth discussion of where the Adria plate was at the time is beyond the scope of this paper. We provide some age spectra of comparison samples to discuss in more detail the location of the Variscan ages.

RC1-6- Another fundamental observation that isn't expanded sufficiently in the discussion is the fact that not a single grain was found that can reasonably be attributed to the Lepontine dome. This was one of the main research questions formulated in the introduction of the paper. Its absence needs to be discussed more fully. Is this absence of a Lepontine signal in the data a disappointment? Not really, although the authors embarked on a study to find where and when the detritus coming from the Lepontine dome enters the Swiss Molasse basin, the answer must be it doesn't.

AC1-5-The spectra from the Lepontine actually match well with our age spectra. See expanded discussion on the sediment source region in section 8.1.

RC1-6 The consistency between the result of the present study and that of Von Eynatten and Wijbrans could have been made a in a little more strongly.

AC1-6- We have included the Von Eynatten and Wijbrans 2003 study in more places throughout the manuscript. We have also increased the discussion on why there are Alpine age detrital mica but not alpine aged zircon.

RC1-7- Probably the most intriguing result is that for the Thun section, which is the section 4 of the Von Eynatten and Wijbrans study, Von Eynatten and Wijbrans do report muscovites with ages consistent with a Lepontine provenance. It now becomes intriguing to speculate as to why the muscovite does show a Lepontine provenance and the zircons do not.

AC1-7- It is suggested that deeper levels of the Lepontine dome were not accessed and that the presence of Alpine age mica (and lack of Alpine age DZ) is attributed to this point. In particular, rocks that are currently exposed in the Lepontine experienced temperatures <600°C between 25 and 20 Ma (Schlunegger and Willett, 1999; Boston et al., 2017). This means that the maximum temperatures of rocks exposed for erosion on the surface at that time were much less. Accordingly, the source rocks did not experience an Alpine metamorphosis that was high enough such as that Alpine aged zircon minerals could grow. Therefore, the detrital zircon minerals in 25 and 20 Ma old Molasse sequences are unlikely to record Alpine ages.

RC1-x The thin films of zircon overgrowth could well have been missed when applying a laser ablation technique.

AC1-x- We do not believe this to be the case, the rims would show up relatively clear with the depth-profile method employed. This was the main reason we used the depth-profile technique.

Reviewer comments from Hilmar Von Eynatten (RC2) and associated Author Comment (AC2)

RC2-1 This culminates in a rather odd statement in the Introduction saying that considerably less attention has been paid to sediment provenance (lines 45-46). In fact, there are not many foreland basins on Earth where such long lasting and detailed provenance work has been done, encompassing almost all available techniques (petrography, heavy minerals, mineral chemistry and isotopes, bulk sediment chemistry and isotopes, Ar/Ar dating, FT-thermochronology, etc.).

AC2-1- We have changed the language at the end of the introduction to reflect the extensive provenance work that has been done in the Swiss Molasse Basin and have added a number of the suggested citations and included additional citations.

RC2-2In terms of detrital chronology, previous studies focused on lower temperature geothermometers. The new data thus fill a gap with respect to zircon U-Pb. This is rewarding but because the previous knowledge has not been clearly summarized, it remains in part unclear which interpretations are new, in contrast, or in line with previous knowledge. Clarifying this would allow for a slightly deeper discussion of the results.

AC2-2- We have added additional discussion of the low temp thermochronometers vs the geochronometers in sections 2 and 8.

RC2-3 There are several more papers on petrography and heavy minerals (HM), a brief summary is given in von Eynatten 2007 (Developments in Sedimentology, 58, 887-905). The HM results are pretty consistent although they do not allow to explain all provenance issues. However, they are not 'inconclusive'. In fact, most advanced provenance studies from the late nineties and the 00's have built on this expertise.

AC2-3- We have added the von Eynatten 2007 citation and included discussion of these points in section 8.4

RC2-Specific Comments RC2-4- lines 45 following:. . ..these studies include zircon FT dating (Spiegel et al. 2000, 2001), underlining and extending on the results from Ar thermochronology. Bulk petrography and bulk chemistry provided details on the Miocene erosion of metamorphic rocks (von Eynatten 2003), supported by heavy mineral chemistry on chrome spinel, garnet and white mica (von Eynatten 2003, 2007; von Eynatten and Wijbrans, respectively). Spiegel et al. 2002 and von Eynatten 2003 have suggested a solution to the epidote issue (lines 262-266).

AC2-4-The reviewer had not seen the newest version where these data were discussed

in much more detail. Chrome spinel data has also been added to the discussion in section 8.4.

RC2-5 line 355: 'no sieving at any point'. After this information, I wonder about the size of the measured zircons. Can you provide any range? Does grain size vary between samples and/or age groups? This is relevant for the problem of size-age relations in DZ geochronology.

AC2-5 To go back and provide statistics on the grain size distribution of the sampled grains would be a major task at this point. We decided to provide a grain size range by looking through all images. Minimum grain size is essentially the diameter of the ablation pit (30 microns) and by briefly looking at images the largest grain on C axis being $\sim$350 microns.

RC2-6 lines 356-358 (now 396): this is the generally accepted approach. Nothing wrong, but typically not all grains are datable/concordant/etc., and thus the dated number is smaller, see figures 4-6, with impact on the uncertainties.

AC2-6 Not sure about the comment here, but this does not affect the reported uncertainties.

RC2-7 lines 456-458 (now 500): grouping of samples of similar unit/area can make sense, especially for purpose of illustration, but should be justified. The authors state that there is 'little variation' within samples from the same units, but what is 'little'? Is this variation insignificant and has been tested, for instance, by K-S? See also next point.

AC2-7- We have added some clarification of what we meant by 'little variation' and have provided some additional details on samples that do show minor changes within a unit.

RC2-8 lines 479-485: why are the two samples amalgamated? They are displayed separately in Fig. 4 and show some contrast, especially regarding proportions of Early vs. Late Variscan.

AC2-8 See comment AC2-7. We have noted changes and still feel these samples are best grouped together for display purposes. If each sample were displayed individually it would drastically complicate the results and figures.

RC2-9 lines 659 (now 724) following (chapter 8.2): The data suggest major break at 22 Ma, most previous studies placed the break with largely similar interpretation at 21 to 20 Ma. Is this within stratigraphic uncertainty, or is there a possibility that the zircon U-Pb signal precedes the low-T thermochron and/or petrographic signals, or is there some other source involved?

AC2-9 We thank the reviewer for bringing this up. The break is actually at 21 Ma. This shift in age is due to the most recent calibration of the magnetopolarity timescale by Lourens et al., (2004), which we have now considered in the revised manuscript.

RC2-10 lines 731-733: see von Eynatten and Wijbrans 2003, von Eynatten 2007.

AC2-10- We have added discussion of these texts throughout.

RC2- Technical corrections:

RC2-11 line 53: please use ‘v’ instead of ‘V’ for von Eynatten, see also References, like ‘von Raumer’.

AC2-11 Corrected throughout

RC2-12 line 61: better add ‘Swiss’ to Molasse Basin, as only a part of the entire North Alpine Foreland (Molasse) Basin is considered in this study.

AC2-5 Added

RC2-13 line 177 (and references): please correct, ‘von’ Blanckenburg

AC2-5 Changed to ‘von’

RC2-14 lines 201-205, figure 2: I suggest highlighting the two cycles graphically in

figure 2.

AC2-5 We have added the two upward coarsening and shallowing cycles to figure 2 and the figure 2 caption.

RC2-15 line 457: abbreviation ‘DZ’ has not been introduced before; should be done along with the first mentioning of detrital zircon in the Introduction.

AC2-5 Got rid of ‘DZ’ abbreviation throughout

RC2-16 line 489: ‘no’ Cenozoic ages. . .

AC2-5 Corrected

RC2-17 line 526 (now 583): number (53) appears inconsistent with figure 5. Please check throughout.

AC2-5 These ages numbers have all been carefully looked through and corrected. The discrepancies arise from the number of ages depicted vs the number of total ages (explained in the caption of figure 4).

RC2-18 line 568 (now 625): delete ‘to’

AC2-5 Corrected

RC2-19 there is some confusion regarding >/<22 Ma and younger/older in figure 7, graphs and caption. Same in text: sentence starting in line 571.

AC2-5 Changed language to “older than” and “younger than” instead of using >22> to avoid confusion.

RC2-20 line 588: ‘are’ instead of ‘and’, I guess

AC2-5 Corrected

RC2-21 lines 596-599: please state something like ‘3 out of X’ to give the reader an idea of the percentages. And/or state the number of available REE profiles per sample/

per time slice in Figure 7.

AC2-5 “n=” added to figure 7 profiles

RC2-22 line 654: was situated . . .

AC2-5 This was already changed in the resubmitted version and is already fixed

Reviewer comments from Anonymous Reviewer (RC3) and associated Author Comment (AC3)

RC3-1-These interpretations which differ from previous studies are well augmented but, however, the author avoid to address some important outstanding questions which arise while reading throughout the text: Why different thermochronometers record this major exhumation phase of the Lepontine dome in the Molasse and the UPb zircons analysis lack this information?

AC3-1 This goes back to the point made by reviewer 1 (Wijbrans) on our evidence of sources from the Lepontine Dome. According to Boston et al. (2017) and also Schlunegger and Willett (1999), currently exposed rocks indicate that they experienced a temperature <600°C between 25 and 20 Ma. This means that the maximum temperatures of rocks exposed for erosion on the surface at that time were much less. Accordingly, the source rocks did not experience an Alpine metamorphosis that was high enough such as that Alpine aged zircon minerals could grow.

RC3-2-What are the implications of using a unique geo/thermochronometers for interpretation of hinterlands evolution over time with respect of multi-proxy thermochronology approach?

AC3-2 I think we outline this well with the new version (i.e. post Spiegel comments).

RC3-3- What is the lag-time between the onset of the Lepontine exhumation and the record of erosion in the Molasse?

AC3-3 Unfortunately, we have no data to constrain this question. However, research

in tectonic geomorphology indicates that the residence time of material within a landscape is much shorter than 1 myr, which is the time span the magnetostratigraphic data is able to resolve. Therefore, we consider that there should be an immediate petrographic signal in the Molasse as soon as tectonic processes exhume deeper seated rocks.

RC3-4- How spatially distributed differences in erosion rates might have biased the observed age distributions?

AC3-4 We thank the reviewer for bringing this up. We do see differences in response signals between the different sections (Thun, Lucerne, Bregenz), and we consider that the data reflect the differences through which tectonic exhumation might have contributed to the various petrographic signals we see in the Molasse. In this sense, yes the differences in exhumation rates and related mechanisms are reflected in the basin at a spatial scale of some tens of kilometers. We do address this point in the manuscript.

RC3-5- The background information is detailed, however, a significant part of the current debate which focuses on how the record of erosion detected from multi-thermochronometers analysis and associated biases is transferred into the foreland sedimentary sequences is missing.

AC3-5- We have expanded this discussion in multiple areas.

RC3-6- Provenance analysis cannot be de-coupled from source information, a compilation of available in-situ ages would improve for example the tectonic map of Figure 1.

AC3-6- We have added samples from Malusa et al. 2013 to show a representation of what the modern Lepontine is composed of. There is too much in-situ data out there to reasonably incorporate it into the paper, so we felt this was a better compromise.

Specific Comments RC3-7- 53-54. Provenance from foreland strata can be used to unravel long-term exhumation from the hinterland, however this need to be coupled with source information. There has been some recent effort in doing so which would need to be acknowledged (e.g. Mineral Fertility: Malusa et al., 2016- modern river analysis correlated with source information e.g. Gemignani et al. 2017). Did the author think about providing averaged in-situ age constraints for the exposed Lepontine unit? These would help them to characterize source provenance in the foreland.

AC3-7- See last comment. We have added modern river samples from Malusa et al. 2013.

RC3 -8- 355. What is the grain size of the analyzed Zr? This need to be specified. There is any relationship between age distribution vs analyzed grains size fraction?

AC3-8- Again see comment to reviewer 2. Grain sizes of zircons were not recorded during analysis but we decided to provide a grain size range. Grains are often broken or rounded, so this information was not documented during analysis. Minimum grain size is essentially the diameter of the ablation pit (30 microns) and by briefly reviewing the images the largest grain is $\sim$350 microns. We add this in Section 4.2.

RC3-9- 403. please correct with superscript 504-505.

AC3-9 Corrected

RC3-10- It would be useful to add a sentence describing how binned age distributions described in section 4 were computed. In particular, you could briefly describe how the age cluster proportions were calculated.

AC3-10 This is the entirety of section 5 and we have added a section on how the percentages in the graphs and text were calculated.

RC3-11- 505. flowing?

AC3-11 Changed to 'Following'

RC3-12- 570. Please double-check groups percentage.

AC3-12 We have gone through these one by one and made sure they are correct. In section 5 we discuss why the percentages are a bit different in the section 6 vs figures 4,5, and 6.

RC3-13- 576-579. Please check age groups proportion and correct percentages, if needed.

AC3-13- Same as last comment.

RC3-14- 679-681. More recent modern river data has been discussed and need to be accounted for the discussion of significant age peaks north of the Periadriatic line.

AC3-14- We have added these ages to figure 1 and include discussion in Section 8.

RC3-15- 682. Interesting observation but needs a substantial comparison with information collected south of the Periadriatic line.

AC3-15- We discuss this in section 8 in more detail.

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